

Measurements of the heavy-flavour nuclear modification factor in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ALICE at the LHC

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Abstract

The heavy-flavour nuclear modification factor R_{pPb} has been measured with the ALICE detector in p–Pb collisions at the nucleon–nucleon center of mass energy $\sqrt{s_{NN}} = 5.02$ TeV at the CERN LHC in a wide rapidity and transverse momentum range, as well as in several decay channels. R_{pPb} is consistent with unity within uncertainties at mid-rapidity and forward rapidity. In the backward region a slight enhancement of the yield of heavy-flavour decay muons is found in the region $2 < p_T < 4$ GeV/c. The results are described within uncertainties by theoretical calculations that include initial-state effects. The measurements add experimental evidence that the suppression of heavy-flavour production observed at high p_T in central Pb–Pb collisions with respect to pp collisions is due to a medium effect induced by the interaction of heavy quarks with the partonic matter.

Keywords: ALICE, heavy-flavour production, in-medium effect, nuclear modification factor, cold nuclear matter effects

1. Introduction

Heavy quarks (charm and beauty) are essential probes of the properties of the medium created in heavy-ion collisions, since they are produced in the early stage of hadronic collisions via scattering processes with large momentum transfer. Heavy-flavour production has been measured via semi-electronic and semi-muonic decays, as well as fully reconstructed D mesons, in pp, p–Pb and Pb–Pb collisions with ALICE [1] at the LHC. In central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, a strong suppression of high transverse momentum (p_T) D mesons and electrons (muons) from heavy-flavour hadron decays was observed at mid- (forward) rapidity [2, 3, 4]. This suppression is interpreted as an effect of parton energy loss in the medium created in heavy-ion collisions. However, a quantitative understanding of the Pb–Pb results requires cold nuclear matter (CNM) effects to be taken into account, which can be accessed by studying p–Pb collisions [5, 6] assuming that a hot and dense extended system is not formed in such collisions. CNM effects are studied using the nuclear modification factor R_{pPb} , defined as

$$R_{pPb} = \frac{1}{\langle T_{pPb} \rangle} \times \frac{dN_{pPb}/dp_T}{d\sigma_{pp}/dp_T} = \frac{1}{A} \times \frac{d\sigma_{pPb}/dp_T}{d\sigma_{pp}/dp_T} \quad (1)$$

where $\langle T_{AA} \rangle$ is the average nuclear overlap function estimated through the Glauber model, which gives $\langle T_{AA} \rangle = 0.0983 \pm 0.0035 \text{ mb}^{-1}$ [7]; dN_{pPb}/dp_T ($d\sigma_{pPb}/dp_T$) is the p_T -differential yield (cross section) in p–Pb collisions and $d\sigma_{pp}/dp_T$ is the p_T -differential cross section in pp collisions; A is the mass number of the Pb nucleus. The value of R_{pPb} is unity in absence of nuclear effects.

2. Heavy-flavour measurements with ALICE

ALICE is the dedicated heavy-ion experiment at the LHC. It allows to investigate heavy-flavour production in several decay channels over a wide rapidity and transverse momentum range. The ALICE detector consists of a set

of central barrel detectors ($|\eta_{\text{lab}}| < 0.9$), a muon spectrometer ($-4.0 < \eta_{\text{lab}} < -2.5$) and global detectors for triggering and event characterization purposes. At mid-rapidity, the Inner Tracking System (ITS) and the Time Projection Chamber (TPC) provide track reconstruction down to very low transverse momentum ($\sim 100 \text{ MeV}/c$) with a momentum resolution better than 4% for $p_T < 20 \text{ GeV}/c$, as well as good impact parameter (distance of closest approach of the track to the primary interaction vertex) resolution [1, 8]. D mesons are reconstructed via their hadronic decay channels and electrons from semileptonic decays of charm and/or beauty hadrons are measured. At forward rapidity, muons from heavy-flavour hadron decays can be measured, since the ALICE muon spectrometer allows to identify muons by requiring that a track reconstructed in the tracking system is matched with the corresponding track candidate in the muon trigger system.

D mesons are reconstructed from their hadronic decay channels $D^0 \rightarrow K^- \pi^+$ (BR = 3.88%), $D^+ \rightarrow K^- \pi^+ \pi^+$ (BR = 9.13%), $D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$ (BR = 67.7%) and $D_s^+ \rightarrow \phi \pi^+ \rightarrow K^+ K^- \pi^+$ (BR = 2.28%). The selection of D meson candidates against the large combinatorial background is based on the reconstruction of decay vertices displaced by a few hundred μm from the interaction vertex, exploiting the $c\tau$ of D^0 , D^+ and D_s^+ , which is about $123 - 300 \mu\text{m}$ depending on the D-meson species. In order to further enhance the ratio between the D-meson signal and the combinatorial background, the measurements of the particle time-of-flight from the collision point to the Time Of Flight (TOF) detector and of the specific energy loss in the TPC gas are used to identify K^\pm and π^\pm [9]. The measurement is performed in the rapidity interval $-0.96 < y_{\text{cms}} < 0.04$ (which is specific for p-Pb collisions) over a wide transverse momentum range.

The electrons are identified with TPC and TOF at low p_T , as well as the TPC and Electromagnetic Calorimeter (EMCAL) at high p_T . The measurement of electrons from heavy-flavour hadron decays at mid-rapidity ($-1.06 < y_{\text{cms}} < 0.14$) requires the subtraction of contributions from several background sources from the inclusive electron distribution. The dominant contribution is from photon conversions in the detector material and Dalitz decays of light neutral mesons (π^0 and η , mainly). These contributions are statistically subtracted by using the cocktail (i.e. a calculation of the background based mainly on measured p_T -differential cross sections of the main electron sources) and invariant mass (i.e. the measurement of electrons from photon conversions and Dalitz decays via low-mass electron-positron pairs) methods [3]. With the high spatial resolution of the track impact parameter measurement, one can isolate the beauty-decay contribution thanks to the much larger lifetime of beauty hadrons ($c\tau \approx 500 \mu\text{m}$) compared to that of charm hadrons and other background sources. The electrons from their semileptonic decays have, consequently, a larger average impact parameter with respect to the primary interaction vertex.

Muons from heavy-flavour hadron decays have been measured at forward (i.e. proton-beam direction, $2.5 < y_{\text{cms}} < 3.53$) and backward (i.e. Pb-beam direction, $-4 < y_{\text{cms}} < -2.96$) rapidity, respectively, by analyzing data collected with different beam configurations. The main source of background in the p_T -differential inclusive spectrum consists of muons from light hadron decays (π^\pm and K^\pm , mainly). This contribution dominates the muon yield for $p_T < 2 \text{ GeV}/c$ and prevents a measurement of muons from heavy-flavour decays at low p_T . At larger p_T the contamination is estimated via Monte-Carlo simulations, as well as with a data-driven method based on the extrapolation of charged hadron yields [10] measured at mid-rapidity with ALICE to forward rapidity.

3. Results

The nuclear modification factors, R_{pPb} , of D^0 , D^+ , D^{*+} and D_s^+ mesons are consistent with each other, and they are compatible with unity within uncertainties [5]. The pp reference cross section at $\sqrt{s} = 5.02 \text{ TeV}$ is obtained by a pQCD-based energy scaling [11, 13] of the p_T -differential cross sections measured at $\sqrt{s} = 7 \text{ TeV}$ [12]. Figure 1 (left) presents the average R_{pPb} of prompt D^0 , D^+ and D^{*+} in $1 < p_T < 24 \text{ GeV}/c$. The R_{pPb} can be described by means of next-to-leading-order (NLO) pQCD [14] calculations, including the EPS09 [15] nuclear modification of the CTEQ6M [16] Parton Distribution Functions (PDF) and calculations based on the Color Glass Condensate (CGC [17]) initial-state prescription. The data are also well described by calculations which include energy loss in cold nuclear matter, nuclear shadowing and k_T -broadening [18]. As demonstrated in Figure 1 (right), cold nuclear matter effects are small for $p_T \gtrsim 3 \text{ GeV}/c$. This indicates that the suppression of D mesons observed in the 20% most central Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$ [2] results from an effect due to the presence of the hot and dense medium.

The R_{pPb} of electrons from heavy-flavour hadron decays in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ is shown in Figure 2 (left). The pp reference is obtained following a strategy similar to the one used for the D-meson analysis. The R_{pPb} is compatible with unity, showing that cold nuclear matter effects are small. The measurement is compared with a pQCD calculation with the EPS09 [15] NLO parameterization of nuclear PDFs. Within uncertainties, the data

can be described by the model predictions. Figure 2 (right) displays the measured R_{pPb} of electrons from heavy-flavour hadron decays together with that of electrons from beauty-hadron decays. The R_{pPb} of electrons from beauty-hadron decays is consistent with unity within uncertainties, and it is also compatible with that of electrons from heavy-flavour hadron decays. The data indicate that the suppression of electrons from heavy-flavour hadron decays observed in the 10% most central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [3] results from a hot medium effect.

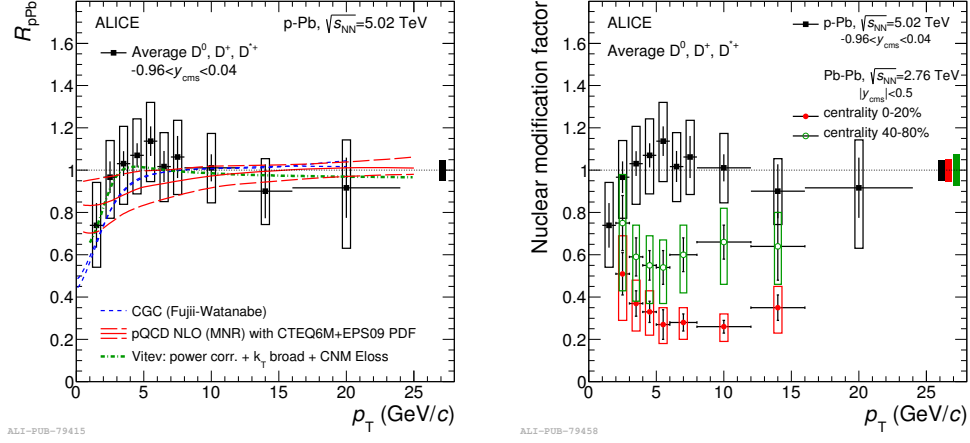


Figure 1. Left: Average R_{pPb} of prompt D^0 , D^+ and D^{*+} mesons as a function of p_T compared to model calculations [14, 15, 16, 17, 18]; Right: Average R_{pPb} of prompt D^0 , D^+ and D^{*+} mesons as a function of p_T compared to the prompt D-meson R_{AA} in central (0-20%) and semi-peripheral (40-80%) Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [3].

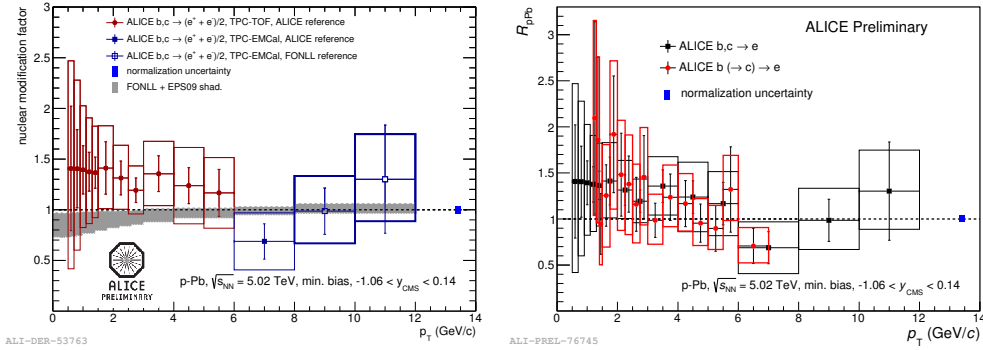


Figure 2. Left: R_{pPb} of electrons from heavy-flavour hadron decays as a function of p_T compared to model calculations [13, 15]; Right: R_{pPb} of electrons from heavy-flavour hadron decays compared to R_{pPb} of electrons from beauty-hadron decays.

The nuclear modification factor of muons from heavy-flavour hadron decays, shown in Figure 3 (left), is measured in the center of mass rapidity domains $2.5 < y_{cms} < 3.53$ (forward rapidity) and $-4 < y_{cms} < -2.96$ (backward rapidity). The pp reference cross section of heavy-flavour hadron decay muons at $\sqrt{s} = 5.02$ TeV is obtained via a pQCD-based energy scaling procedure [13] (i.e. calculated taking as input the p_T -differential cross sections measured at $\sqrt{s} = 7$ TeV [19]), performed at forward and backward rapidity, respectively. This procedure is used to obtain the p_T -differential cross section up to 12 GeV/c. In order to measure the R_{pPb} in a wider transverse momentum range, the p_T -differential cross section in pp collisions at $\sqrt{s} = 5.02$ TeV was extrapolated to higher p_T using the spectrum predicted by FONLL scaled to match the obtained pp reference in the range $6 < p_T < 12$ GeV/c. The R_{pPb} measured at forward rapidity is consistent with unity within uncertainties. R_{pPb} at backward rapidity is slightly larger than unity in the range $2 < p_T < 4$ GeV/c and close to unity at higher p_T . This supports the previous observation that the suppression measured in the 10% most central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [4] results from hot and dense medium effect.

Another way to quantify cold nuclear matter effects is to study the forward-to-backward ratio defined as the cross section measured at forward rapidity with respect to the one at backward rapidity. The main advantage of using such a ratio is that the pp reference and the nuclear overlap function cancel. The drawback of this approach is the limited

statistics, because the common y_{cms} interval covered at both forward and backward rapidity is small (~ 0.57 units).

$$R_{\text{FB}}(2.96 < |y_{\text{cms}}| < 3.54) = \frac{d\sigma^{\text{forward}}/dp_T(2.96 < y_{\text{cms}} < 3.54)}{d\sigma^{\text{backward}}/dp_T(-3.54 < y_{\text{cms}} < -2.96)} \quad (2)$$

The measured R_{FB} is presented in Figure 3 (right). It is systematically smaller than unity in the range $2 < p_T < 4$ GeV/c and close to unity at higher p_T . This is well reproduced by a pQCD calculation including the EPS09 [15] NLO parameterization of nuclear PDFs [14] in the range $2 < p_T < 16$ GeV/c. The R_{pPb} measured at backward rapidity is slightly underestimated by such theoretical calculations at low p_T .

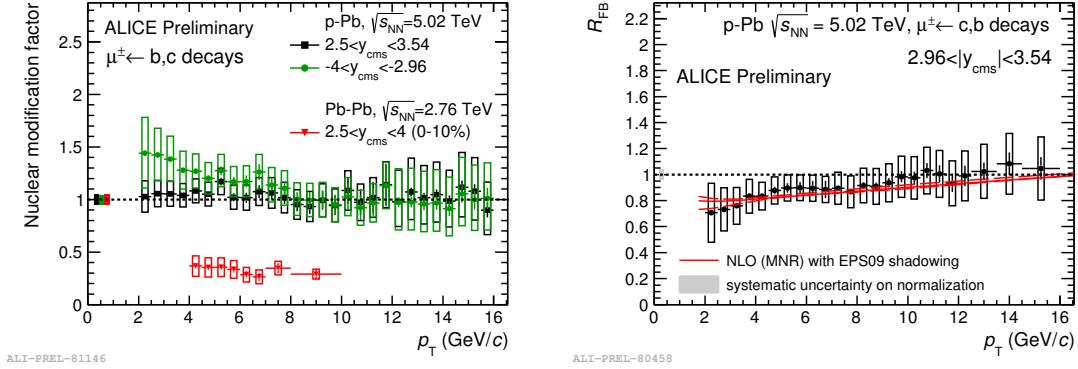


Figure 3. Left: R_{pPb} of muons from heavy-flavour hadron decays as a function of p_T at forward rapidity ($2.5 < y_{\text{cms}} < 3.53$) and backward rapidity ($-4 < y_{\text{cms}} < -2.96$), compared to the R_{AA} for muons from heavy-flavour hadron decays in the 10% most central Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV [4]; Right: Forward-to-backward ratio R_{FB} of muons from heavy-flavour hadron decays compared to a model calculation [14, 15].

4. Conclusions

The nuclear modification factor of heavy-flavour production has been measured in a wide rapidity and transverse momentum range, as well as in several decay channels, in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV with ALICE. The R_{pPb} results provide evidence that cold nuclear matter effects are small, showing that the strong suppression observed in central Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV is a final state effect due to in-medium parton energy loss.

Acknowledgments

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